TECHNICAL REPORT
71-43-ES

MORPHOMETRY OF LANDFORMS: DRUMLINS

by
H. Frank Barnett, Jr.
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U.S. ARMY NATICK LABORATORIES
Natick, Massachusetts 01760

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FOREWORD

From late 1968 to mid-1970 the Earth Sciences Laboratory of U. S. Army Natick Laboratories measured slopes on drumlins in the northeastern United States and in southern Germany. This report outlines the field measurement techniques and summarizes the data as a contribution to the general bank of ground-truth information fundamental to descriptive classification of terrain for military and scientific purposes.

Drumlins were chosen for study because these glacially deposited hills are distinctive locally accessible landforms useful in developing and evaluating a methodology for describing any terrain quantitatively. They are of military interest as factors affecting visibility, mobility, fields-of-fire, and defilade.

The work reported here is a step toward classifying glaciated terrain quantitatively by describing component landforms individually. Additional field measurements of associated landforms will establish a base from which classification of broader areas can be made from airphotos or topographic maps. The same methodology will be applicable to descriptive classification of terrains other than glacial.

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13. ABSTRACT

Lengths, widths, heights, and asymmetries of 55 drumlins in Massachusetts, New York, and southern Germany are derived from 46 miles of traverse. Slope gradients and lengths were measured in the field as a basis for quantitative description of a glacial landform significant to military operations and materiel.

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MORPHOMETRY OF LANDFORMS: DRUMLINS

Purpose and Application

The data of this study are intended to provide ground-truth control for modeling terrain in glaciated regions dominated by drumlins. The data are a contribution to the bank of detailed information essential to development of regional quantitative terrain descriptions guiding design, test, and use of military materiel. The field and data-analysis techniques used illustrate a methodology for landform description.

Augmented by field measurements of associated landforms, these data can form the basis for quantitative description of broad tracts of glacially deposited terrain throughout the Northern Hemisphere.

Glaciated areas are significant to military operations. They occur over 33.6 to 54.8 million square kilometers (12 to 20 million square miles) of the earth's surface (Charlesworth, 1957, p. 704; see tabulation below). More than half of the areas in the Northern Hemisphere are in North America, and more than half of the remainder in northwest Europe.

Region	Surface Area (million sq km)		
	Investigator		
	Antevs	Penck	Valentin
North Europe and west Siberia	3.3	13.0	10.2
East and southeast Siberia)		3.2	1.5
Central Asia)	3.3	0.5	1.5
Faeroes and Iceland, etc.		0.1	0.4
Greenland	2.0	3.0	2.3
North America	11.5	16.7	15.8
Temperate and Tropical latitudes		2.4	0.1*
Patagonia and Antarctic Islands		1.4	1.0**
Antarctic continent	13.5	14.5	14.0***
Totals	33.6	54.8	46.8

*Australasia **South America ***Antarctica

No estimate is available to suggest the total number of drumlins. They are, however, more widespread than is generally recognized.

Quoting from Charlesworth (1957), p. 393: "British drumlins are especially well developed in County Donegal, County Mayo and in north-east Ireland where they extend from the Ards Peninsula to the Shannon and County Louth and constitute one of the biggest continuous drumlin countries in the world; in Galloway, the Tweed Valley and the Midland Valley in Scotland; in Wensleydale, the neighborhood of Kendal, Oxenholme and the Ribble Valley, between Hellifield and Skipton, in the Vale of Eden and Solway area in England; and in Anglesey and the Wrexham district in north Wales. On the mainland of Europe . . . they are found in various parts within the Alpine glaciation and, relatively rarely, in north Germany, in Holland, and in Jutland and Denmark. They have been recorded from the lands east and southeast of the Baltic and from Poland, the Ukraine and Fennoscandia (e.g., Narke, Ostergotland, Vastergotland, Finland). Forms have been identified with them from central France, the Dinaric Alps, Tienshan, Siberia, Novaya Zemlya and China.

"North American drumlins are grouped mainly in five areas: (a) Manitoba and Athabasca; (b) New England, ranging from Ontario, New Brunswick and Nova Scotia (2300 in the southwest) through south Maine and New Hampshire (c. 700) to Connecticut and Massachusetts (c. 1800), including 180 about Boston; (c) Michigan and Wisconsin, of whose 5000 drumlins 1400 are situated in the southeast; and (d) central Western New York. This state has one of the most remarkable groups in the world; the belt which is 35 miles (56 km) broad and 140 miles (c. 225 km) long between Lake Ontario and the Finger Lakes and rises to 1700 ft (518 m), comprises 5000 sq. miles (c. 13,000 sq. km) and over 10,000 drumlins. Where set close, they are 20-35 per 4 square miles, though 5 to the square mile is common and 3 is the average . . . A fifth area occurs in British Columbia where they probably number several hundred thousand."

Results

Slopes were measured on 55 drumlins in classic areas of drumlin occurrence - north-central Massachusetts, central-western New York, and southern Germany. Gradients and lengths of 3200 slope segments (slope-distance increments) totalling more than 46 miles of traverse, recorded on EAM punch cards, are the data from which quantitative expressions of drumlin size, shape, and asymmetry have been derived.

Limitations of the Study

Although the 46 miles of walked traverses on drumlins appear to be the most intensive field measurements available, the data express an exact range of values for only the 55 features measured. It is reasonable to assume a closely similar range for the drumlins associated with those measured; but it cannot be assumed that the range is more than a first approximation for all drumlins of the world.

Features with smooth oval, elliptical, or rounded ground plans were chosen for measurement whenever possible, in the hope that the information might thus serve both military and academic glaciological interests. Sampling, therefore, was not random, but unpredictable circumstances of accessibility and cultural development forced a measure of randomness upon final field selection.

The study considers only the geometry of drumlin surfaces, rather than cover, composition, or internal structure.

Within the limitations of the sampling, the density of traverse lines (four per feature), and the precision of the measuring instruments (gradients to one degree, distances to two percent of actual), the data are accurate.

Definitions

Drumlins are oval, elliptical, or elongated hills formed under thick ice sheets as accumulations of clayey stoney material compacted and streamlined by pressure of the moving ice. Long axes of the features are parallel with major directions of ice movement and, approximately, with orientations of scratches on associated bedrock overridden by the ice. The material of drumlins is generally unlayered and directionless, although bedrock knobs, waterlaid sand and gravel, and stress-layering may be included. Thin surface soils on the clayey substratum usually support only pasturage, fodder, orchard, and tree crops.

Drumlins usually occur as "fields" - a large number of features in a group, close together and sometimes coalescing near their bases. Among the better-known fields of North America are those in Massachusetts, New York, Wisconsin, Manitoba, Ontario, British Columbia, and Saskatchewan. In Europe, such groupings are found principally in Germany, Ireland, England, and Switzerland.

Drumlin shapes range widely, to include smooth oval hills, almost-round mounds, and elongated ridges; some are double-tailed, have undulating crestlines, or show other irregularities in plan or profile. Heights range from 20 feet to at least 200 feet; lengths, from several hundred feet to a few miles. In spite of their irregularities, drumlins meet Barton's (1893) ideal as "the most symmetrical and graceful hill that nature produces".

Historical Background

Earliest recorded interest in the picturesque, gracefully rounded hills now known as drumlins was in Ireland and Scotland, in the "basket-of-eggs", "bag-of-potatoes" countrysides. Bryce used the term drumlin in 1833, Close brought it into glacial literature in 1866; W. M. Davis introduced it into America in 1884, thereby retiring more colorful but less objective terms such as sow-back, whale-back, horse-back, mammillary or elliptical hill, lenticular hill, parallel ridges, drift hill.

Sir James Hall in 1815 wrote of hills near Edinburgh, commenting that their rubbish-like irregular composition must result from some cause other than "ordinary detritus and wearing away of the land"; he favored earthquake waves as that cause. M. H. Close, writing in 1866 of rocks near Dublin, made the first clear reference to drumlins as directly dependent upon glacial action for their form; their parallelism with neighboring striae on bedrock led him to this interpretation.

The ensuing several decades of the nineteenth and early twentieth centuries saw considerable interest in drumlins as part of the glacial scene. Nearly all the investigations, however, were qualitative surficial studies directed toward explanation of possible origin; quantitative description was only rarely a product of the investigations. Ebers' (1926) collection of drumlin shape and size data was one outstanding such product, although many of these data are for broad ranges and mean values which are imprecise numerical descriptions. Actual field measurements of drumlin slopes seem never to have been published.

Quoting from Smalley and Unwin (1968): " . . . although much has been written about drumlins, very little hard fact has emerged. Only recently, in accordance with the general trend in geomorphology, has the quantitative investigation of drumlins and drumlin fields been undertaken. Chorley (1959) has given a meaningful interpretation of the shape of drumlins; Reed and others (1962) have measured distributions and orientations, and Vernon (1966) has measured spacings and distribution; these three papers represent the basis of the new approach to the problem of drumlin formation."

The data of this report contribute "hard fact" descriptions of the three-dimensional form of drumlins.

Study Areas

Investigations were conducted in areas long accepted by geologists as drumlin fields, to permit correlation of measurement data with published information and to minimize identification and verification of features in the field.

Sampling density (number of features measured relative to the number occurring in a definable area) differed greatly in the several areas studied. In Germany the drumlin fields were relatively small and clearly separable from adjacent non-drumlin landscapes; in New York the great number and extent of drumlins make a quantitative expression of sampling density almost meaningless; in Massachusetts, sampling was limited to an apparent local field. The following tabulation is, therefore, illustrative only with the above limitations in mind:

Area	Approx. Total Drumlins	Drumlins Measured	Percent of Total
Hudson (quadrangle), Mass.	56	17	30
Weedsport (quadrangle), N. Y.	71*	9	13
Eberfing, Germany	45	13	29
Bodanrück, Germany	70	10	14
Cato (quadrangle), N. Y.	85*	1	--
Cayuga (quadrangle), N. Y.	90	2	--
Rosenheim, Germany	15	3	20

*Reed and others, 1962.

The Hudson Area, Massachusetts, (Figure 1), west of Boston and including the town of Hudson, occupies approximately the southern half of the Hudson 7 1/2-minute topographic series map of the U. S. Geological Survey (1966) at a scale of 1:24,000 and a contour interval of 10 feet.

Alden (1924) investigated drumlins of the Hudson area as early as 1906. More recently, W. R. Hansen (1956) published Geological Survey Bulletin 1038 discussing the geology of the Hudson and adjacent Maynard quadrangles. Drumlins measured in the Hudson area were chosen from Hansen's surficial geology map.

The Weedsport Area, New York, (Figure 2), transected east to west by the valley of the Seneca River and including the town of Weedsport, is depicted topographically on the Weedsport 7 1/2-minute topographic series map of the U. S. Geological Survey (1954) at a scale of 1:24,000 and a contour interval of 10 feet.

The Cato and Cayuga Areas, New York, adjacent to Weedsport and part of the same large drumlin field, are also shown on U. S. Geological Survey topographic 7 1/2-minute maps. (Figures showing individual drumlins measured are not included in this report because only three widely separated features were measured.)

The New York areas were recognized as a drumlin field at least as early as 1882. A recent map and airphoto analysis (Reed, Galvin, and Miller, 1962) of 71 features in the Weedsport quadrangle presents data on form, orientation, and spacing which are amenable to correlation with the field data of this report.

The Eberfing Area, Germany, (Figure 3), southwest of Munich and Würm (Starnberger) See and including the towns of Eberfing and Marnbach, is on the Seeshaupt and Iffeldorf topographic sheets published by the Bayerisches Landesvermessungsamt (1959) at a scale of 1:25,000 and a contour interval which varies from one to ten meters according to the steepness of the slopes. (Figure 3 is from a 1:50,000-scale map.)

Named by Rothpletz (1917), the Eberfing Drumlin Field has been well documented by several glaciologists. Ebers (1925, 1926) referred to it as "one of the most beautiful drumlin fields of the continent".

The Bodanrück Area, Germany, (Figure 4), occupying the southeastern half of the peninsula at the western end of Boden See (Lake Constance), is on the Überlingen topographic sheet published by the Landesvermessungsamt Baden-Württemberg (1957) at a scale of 1:25,000 and a contour interval of 10 meters with 5-meter supplementaries. (Figure 4 is from a 1:50,000-scale map.)

The Bodanrück area ranks a close second in glacial literature as the most often mentioned drumlin field of Germany. The maximum concentration of drumlins is between the towns of Dettingen and Wollmatingen. There are some smoothly rounded features which Ebers referred to as "real gems."

The Rosenheim Area, Germany, east of the Inn River and northwest of Simssee, extends from the city of Rosenheim to the village of Vogtareuth. The area is shown on the Rosenheim topographic sheet published by the Bayerisches Landesvermessungsamt (1961) at a scale of 1:50,000 and a contour interval which varies from 2-1/2 to 10 meters according to the steepness of the slopes. (A figure showing individual drumlins measured is not included in this report because only three features were measured.)

This small drumlin field was mentioned by the glaciologists Ebers and Früh principally to point out the apparently incomplete, less developed forms of the features. Field observations during this study confirmed the rather unusual shapes of most of the features, so only three were measured. Although these three drumlins may be incompletely developed, they are, nevertheless, bona fide representatives of the drumlin population of the earth.

Field Methods

In Massachusetts, individual drumlins measured were selected by reference to a published geologic map and in consideration of their accessibility. In New York and Germany, they were selected as accessible, oval or elongated, arched, non-bedrock hills occurring in areas referred to in geologic literature as drumlin fields. Irregularly shaped features were not included, as mentioned under Limitations of the Study. A given drumlin field was sampled across its extents, parallel and normal to the direction of ice movement, where possible. Drumlins of different sizes were chosen to reflect roughly the range of sizes in an area.

Terms adopted to standardize field reporting define drumlin slope positions by reference to the known direction of ice movement (see Figures 6, 7): the longitudinal axis parallels that direction and is the longest dimension; looking along that axis toward the source area of the ice sheet, slopes normal to the axis are left or right; the end of the feature toward the ice source is the stoss (proximal) end; and the opposite end, the lee (distal) end. The highpoint of the drumlin was usually identified in the field. Cross (transverse) traverses, thus, are referred to as stoss cross, highpoint cross, and lee cross.

The direction of the first (longitudinal) traverse was determined by a line drawn through the oval or ellipse enclosed by the uppermost closed topographic map contour. Slope measuring usually began at the highest point of the feature as determined in the field. Three cross traverses were made normal to this longitudinal line, one through the highpoint and one across each flank. Those on the flanks were approximately midway down the slopes, but the actual locations were chosen to avoid obviously altered topography and obstructions.

Traverse directions were maintained with a Brunton compass ("pocket transit") read to whole degrees. Slope angles were measured with a hand-held Abney level, also read to whole degrees.

Figure 1 Drumlins measured in the HUDSON AREA, Massachusetts (shaded). Scale approximately 1:50,000, contour interval ten feet.

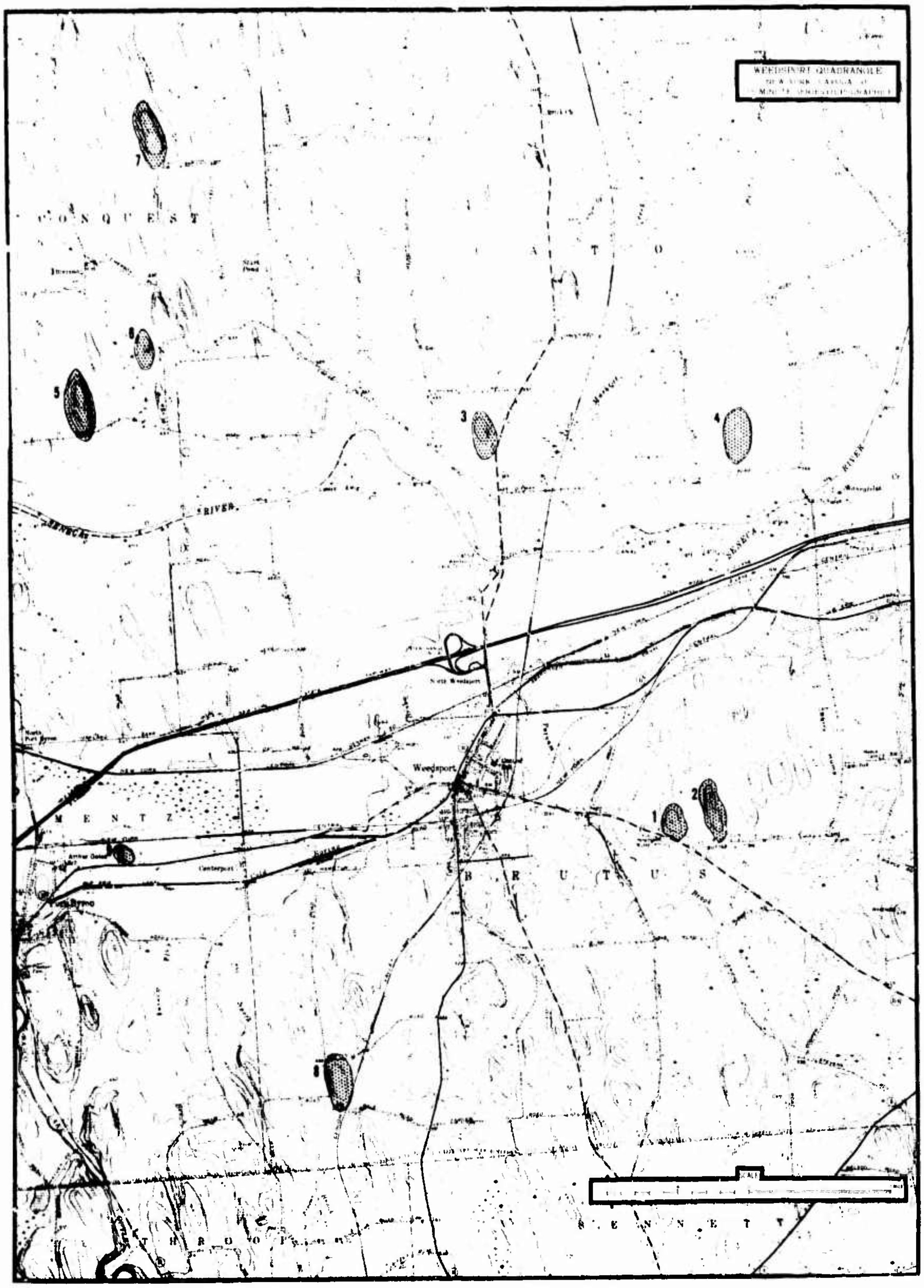

Figure 2 Drumlins measured in the WEEDSPORT AREA, New York (shaded).
Scale approximately 1:50,000, contour interval 20 feet.

Figure 3 Drumlins measured in the EBERFING AREA, Germany (shaded). Scale approximately 1:37,500, contour interval 1-10 meters.

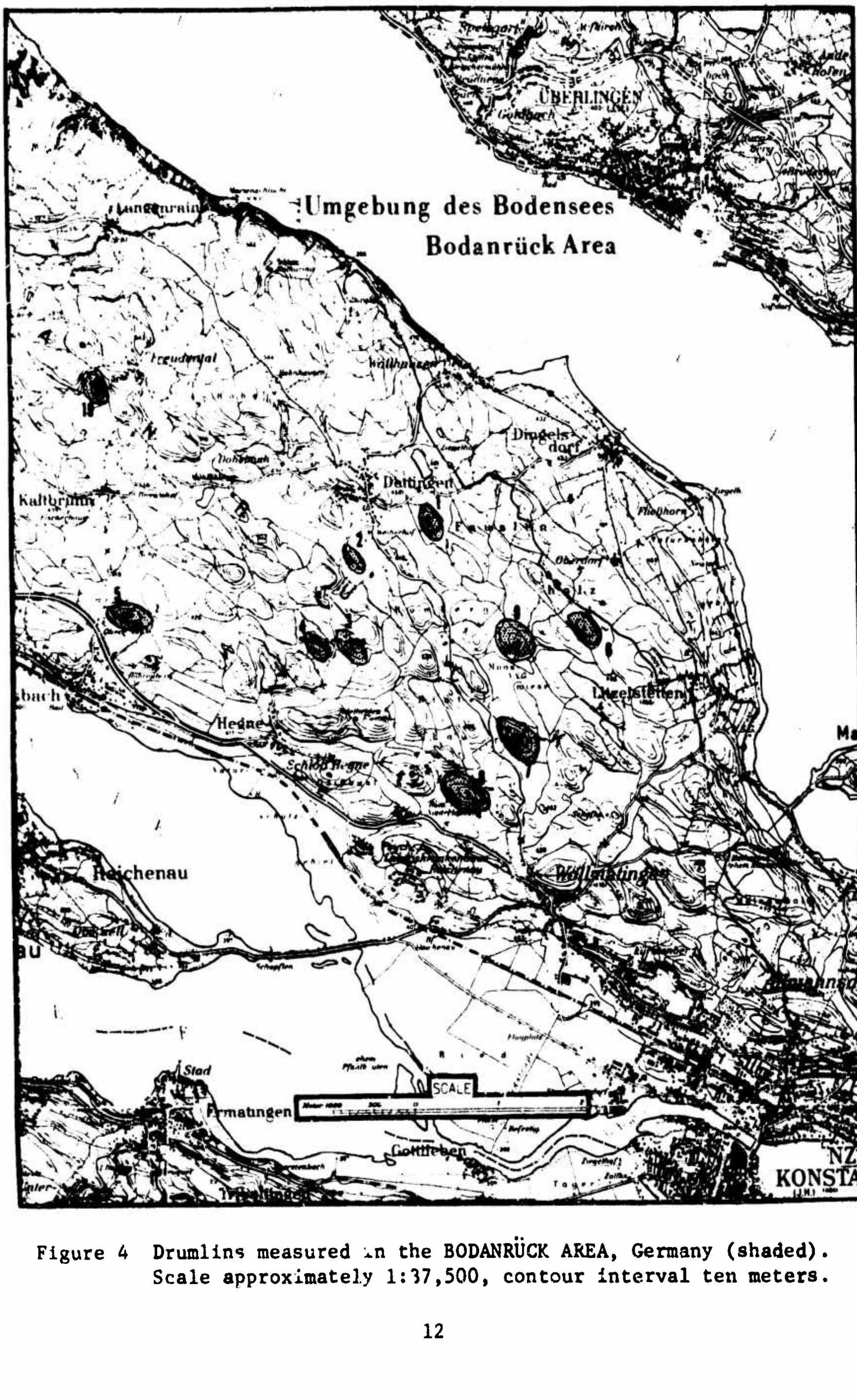

Figure 4 Drumlins measured in the BODANRÜCK AREA, Germany (shaded). Scale approximately 1:37,500, contour interval ten meters.

Slope distances were measured with a superimposed-image optical rangefinder having a parallax base length of 9-3/4 inches, calibrated in one-foot graduations from 17 to 50 feet and in gradually coarser graduations to a maximum range of 1000 feet. The rangefinder, checked against a steel tape at the beginning of each field day, is accurate to about two percent if the ranging target (a second member of the team) is clearly visible. Distances sighted ranged from 17 feet in heavy vegetation to about 200 feet in the open, averaging about 70 feet for all of the study. Every apparent break in slope was taken as a measurement station, and long uniform slopes were divided as appropriate.

Data Compilation and Interpretation

Although the actual sequence and directions in which slopes were measured varied as expedient in the field, the data have been compiled on EAM cards as if collected from stoss to lee along the longitudinal axis, and from left to right on the cross traverses (see definitions under Field Methods). The data do not include slopes considered, in the field, to be off-feature surfaces - slopes near the probable base of the feature which flatten upon adjacent fill or steepen into an erosional depression.

It is often impossible to define in the field the exact extents of drumlins. Where do drumlin slopes end and ground moraine, post-depositional fill, or erosion begin? The question becomes repetitive in areas such as north-central Massachusetts where fields of drumlins occur interspersed with bedrock features. For military evaluation, however, the few data in this report which may be for slopes beyond the actual limits of drumlins cannot noticeably affect slope-gradient and relief statistics.

Each slope segment (slope-distance increment) is recorded on a single EAM punchcard. Included on the card is information as to traverse location and orientation, as well as separation of data into stoss, lee, left, or right slopes (of particular use in describing asymmetry of the drumlin).

Sums of slope distances by degrees for each geographic area visited are the basis for the statistics presented in the accompanying tables and graphs. Slope-gradient frequencies (Table I and Figure 5) are, therefore, given as percents of total traverse distances (not reduced to horizontal).

Table 1. Slope-gradient frequencies as percent of total traverse distances, by degrees

Slope (°)	Hudson	Weedsport	Eberfing	Bodanrück	Cato/Cayuga	Rosenheim
0	2.85	2.03	1.11	1.66	7.26	7.55
1	6.49	6.81	3.54	4.74	17.44	10.85
2	8.03	10.89	5.00	4.79	7.68	14.75
3	8.18	9.97	8.42	4.57	7.56	6.61
4	9.45	9.73	6.84	5.03	8.97	21.48
5	9.32	9.82	8.87	5.66	5.16	13.53
6	9.41	8.86	6.10	6.13	6.61	10.04
7	8.13	1.97	6.70	3.94	5.71	1.53
8	6.52	5.93	9.11	6.38	1.18	3.37
9	6.27	4.85	7.44	4.72	5.16	1.84
10	5.71	3.56	8.10	6.85	1.19	2.66
11	5.31	2.76	5.38	5.65	0.45	0.48
12	4.12	5.95	4.84	6.44	2.37	1.93
13	2.05	2.35	4.04	6.24	2.48	----
14	1.94	2.33	3.47	3.57	1.37	1.30
15	1.96	2.46	2.50	5.04	3.21	----
16	0.90	1.63	1.86	4.07	2.09	----
17	0.71	1.32	1.07	3.32	2.27	----
18	0.90	1.32	1.29	2.44	3.67	1.12
19	0.49	1.15	0.48	2.09	1.71	----
20	0.54	0.94	0.90	1.19	2.47	----
21	0.48	0.52	1.22	1.80	1.46	----
22	0.20	1.02	0.61	0.83	0.41	----
23	----	0.79	0.25	1.18	0.43	0.45
24	0.04	0.17	0.46	0.36	0.36	----
25	----	0.24	0.22	0.16	0.30	0.51
26	----	0.24	0.11	----	0.56	-----
27	----	0.23	----	0.04	0.47	----
28	----	0.16	0.07	----	----	----
29	----	----	----	0.03	----	----
30	----	----	----	0.08	----	----
	100.00	100.00	100.00	100.00	100.00	100.00

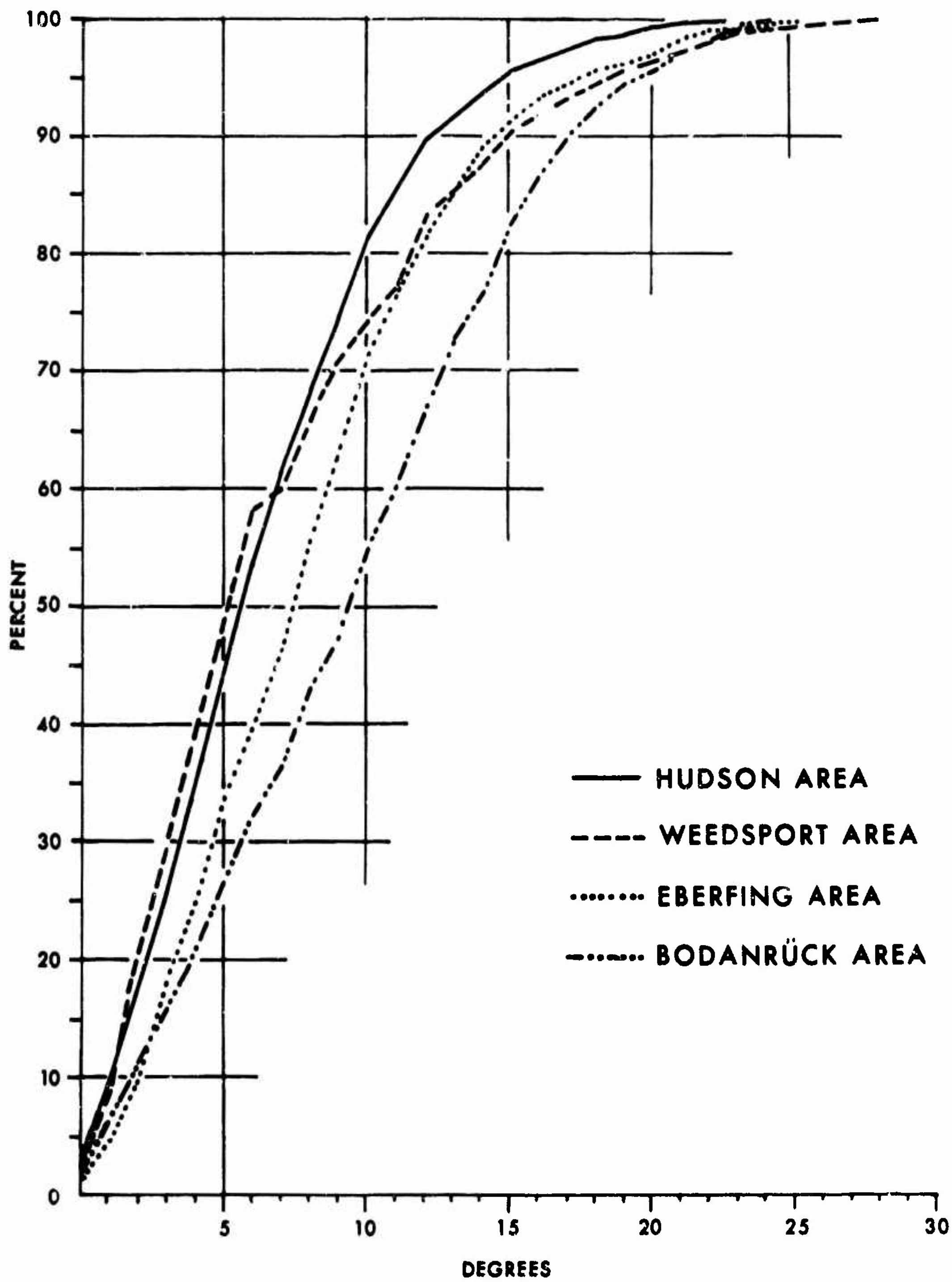

Figure 5 Cumulative slope-gradient frequencies as percent of total traverse distances, by degrees.

Values describing ground-plan dimensions of drumlins (Table 2 and Appendices A-E; refer to Figures 1-4 for locations) - length, width, axial ratio, height, orientation, and asymmetry - are derived from horizontal distances calculated from the summed slope distances. Drumlin length is the total of stoss and lee lengths. Drumlin width is the projection of the highpoint cross. Axial ratio results from division of the length by the width.

Drumlin heights are computed trigonometrically as the mean of both left and right slopes along the highpoint cross, and lee and stoss slopes along the longitudinal axis. Heights along the other transverse axes are shown on the tables but were not used.

Compass orientations of the longitudinal axes are in degrees True on a 360-degree azimuth circle, always in the north half of the circle. There is, therefore, no expressed relationship between orientation and the direction of regional movement of glacial ice. (The ice moved southward in North America and northward in southern Germany.)

Longitudinal asymmetry derives from division of lee length by stoss length; transverse asymmetry by division of total right slope lengths by left slope lengths.

The number of drumlins measured in the Cato and Cayuga, New York, quadrangles, and in the Rosenheim, Germany, area (total of six) is too few to characterize the drumlin fields of which they are a part. No cumulative slope-gradient frequency curves, therefore, are shown for them on Figure 5. The measurement data, however, are valid descriptors augmenting drumlin data in general.

The data of this study have not been interpreted for evaluation of effects on military materiel or operations. They are available on EAM punch cards at Natick Laboratories and interpretations for terrain modeling, design, mobility, etc. can be made from them as specific requirements arise with concerned agencies or activities. The section on Recommendations for Further Studies suggests lines of investigation for which the data can be quantitative inputs.

A summary of mean drumlin dimensions is included in the body of the report (Table 2); dimensions of individual drumlins are in Appendices A-E, in feet.

		HUDSON	WEEDSPORT	EBERFING	BODANRÜCK	CATO/ CAYUGA	ROSENHEIM
		Mass.	New York	Germany	Germany	New York	Germany
SAMPLING RECORD							
No. of drumlins measured		17	9	13	10	3	3
Distances measured: (ft)	long.	32,684	16,069	23,436	14,903	11,115	7,334
	transv.	56,601	20,613	30,282	19,003	6,768	6,253
DIMENSIONS							
Mean length	feet	1,923	1,785	1,803	1,490	3,705	2,445
Mean width	feet	1,284	827	879	776	792	916
Mean axial ratio	$\frac{\text{length}}{\text{width}}$	1.54	2.19	2.18	1.98	4.66	2.80
Mean height	feet	100	80	94	96	107	52
Long. axis orientation	° true	347	347	335	315	344	034
Asymmetry, longitudinal	$\frac{\text{lee}}{\text{stoss}}$	1.00	1.29	1.65	1.22	1.63	1.09
Asymmetry, transverse	$\frac{\text{right}}{\text{left}}$	1.18	1.18	1.37	1.34	1.16	1.09

Table 2. Summary of mean drumlin dimensions, by areas

Explanation of Selected Drumlin Profiles

Profiles across two drumlins are shown with inset enlargements from topographic sheets.

The feature portrayed in Figure 6, from near Eberfing, Germany, was selected as an example of an apparently little-modified drumlin. It is isolated from nearby hills by a considerable expanse of level ground and is not obviously impinged upon by any present drainage-ways. It is, perhaps, more representative of an assumed original, "pure" form than is any other drumlin measured in the several areas.

The drumlin of Figure 7, from the Hudson, Massachusetts, area, appears to have a relatively little-eroded longitudinal profile, but the transverse profiles may have been shortened and steepened by channeling suggested by the pattern of adjacent swamps. The Hudson example illustrates an occurrence common in the irregular topography of north-central Massachusetts, and cautions against assuming near-original shapes for drumlins in any area for which the detailed geomorphic history is unknown.

Military use of the data of this report will not be concerned with the geomorphic complexities implied in the two drumlin profiles. Academic use, however, must recognize that the entire form and volume of a drumlin as originally laid down can never have remained intact.

One longitudinal and three transverse profiles are shown for each drumlin. The solid-line surface traces indicate apparent extents of the features, generally terminated in the field at abrupt changes or reversals in slope; dashed portions (not included in data compilation) indicate total traverse lengths. Vertical tick-marks on the traces are actual measurement stations. At the bases of the profiles are reference lines at a common elevation equivalent to that of the lower end of the longitudinal profile. Small circles on the profiles indicate common points of intersection: to visualize the feature three-dimensionally, rotate profiles upward on their respective basal reference lines. Traverses are always numbered in Roman numerals in the following order: longitudinal, I; highpoint cross, II; stoss cross, III; and lee cross, IV.

The topographic insets use standard symbols. The longitudinal line parallels that of the accompanying profile, regardless of actual compass orientation. The elevations shown for contour lines indicate the interval.

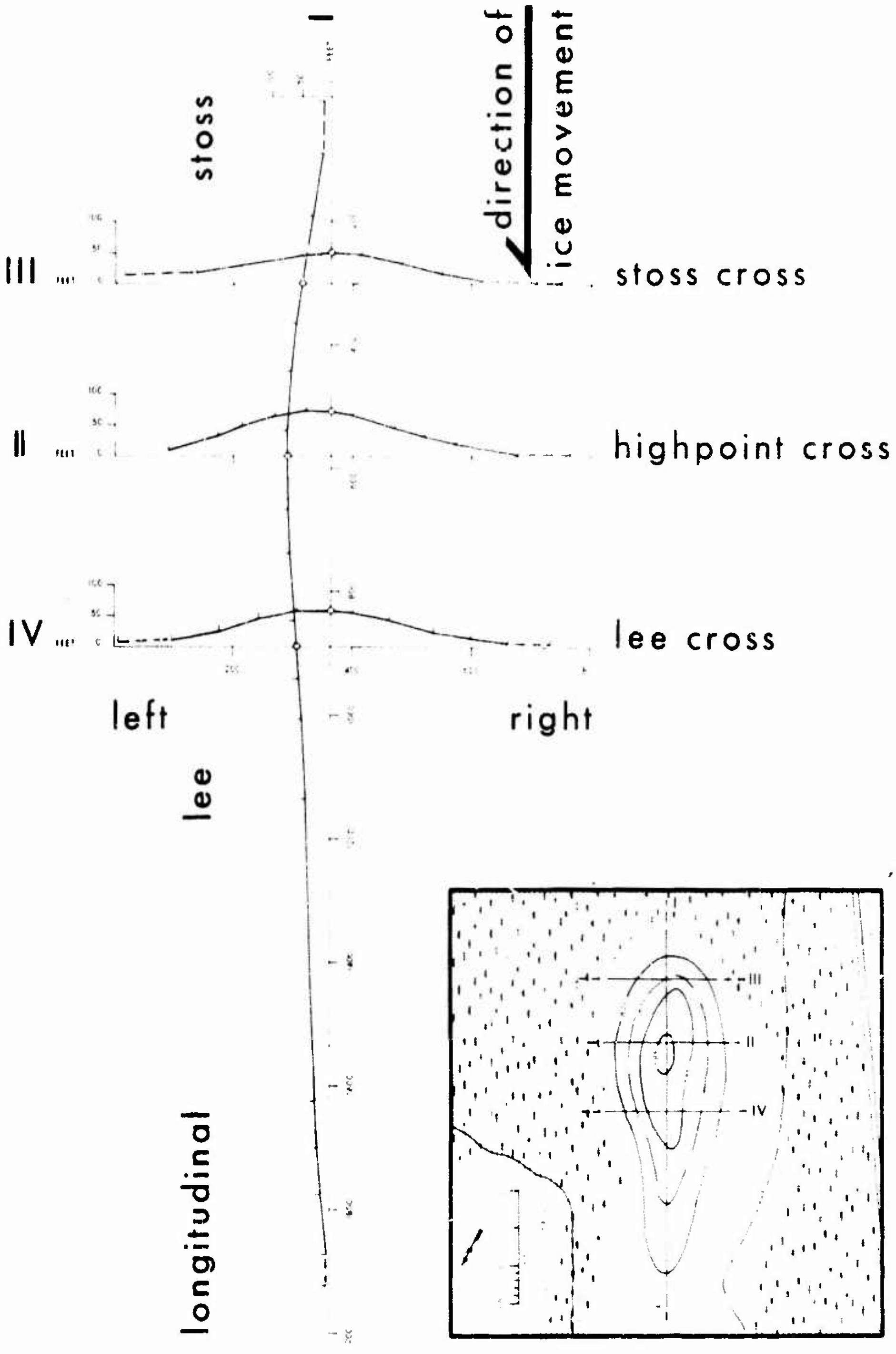

Figure 6 Field-measured profiles of drumlin in the Eberfing Area, southern Germany. (Feature No. 7, Fig. 3). No vertical exaggeration. Topographic map at right not to same scale.

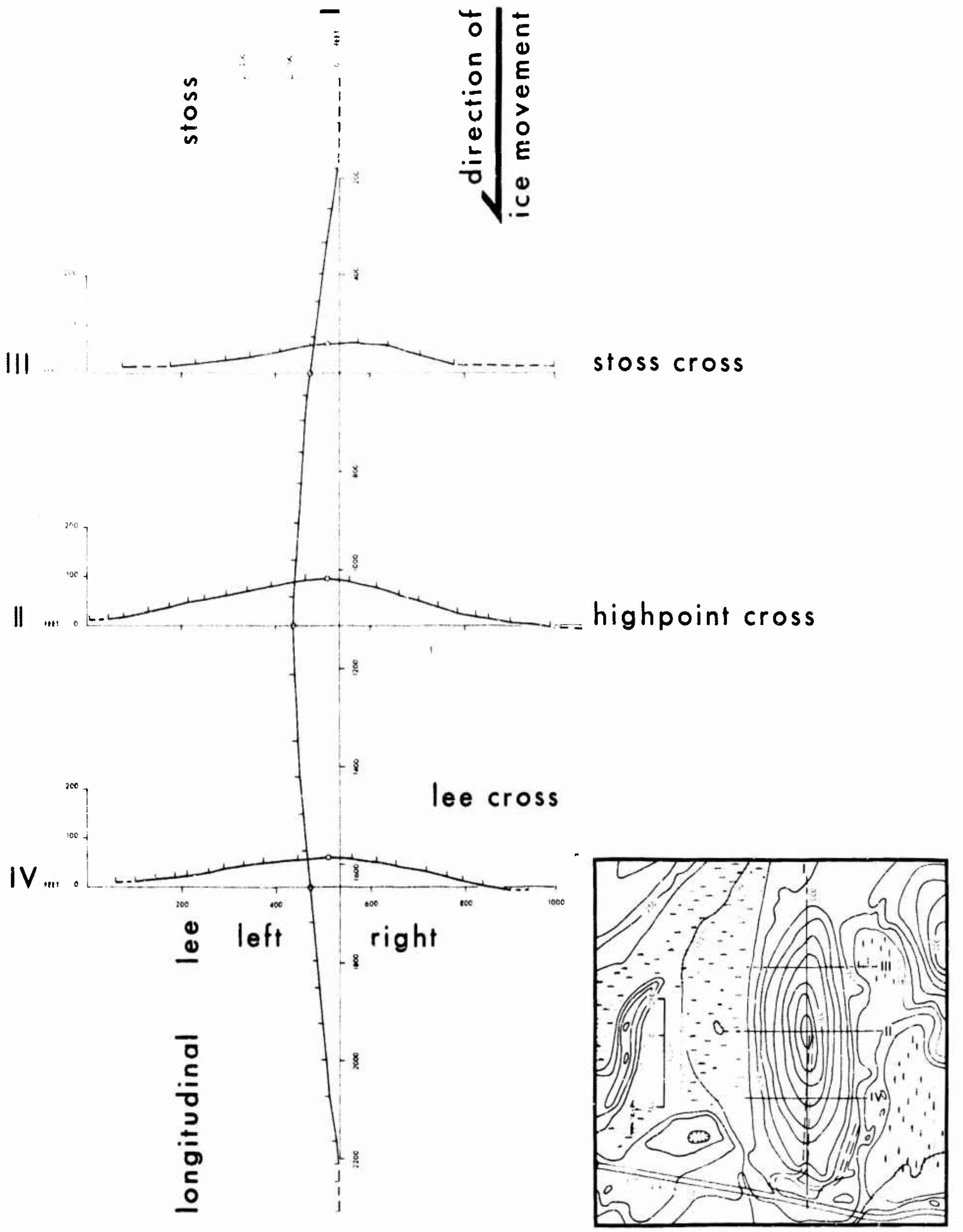

Figure 7 Field-measured profiles of drumlin in the Hudson Area, Massachusetts. (Feature No. 5, Fig. 1). No vertical exaggeration. Topographic map at right not to same scale.

Recommendations for Further Studies

Field ground-truth data are fundamental to the development of regional quantitative terrain classifications. Detailed knowledge of representative component landforms of a given terrain establishes a range of values to control description and evaluation of similar terrains at other scales and for specific purposes. Further studies should include field sampling of other terrain types immediately pertinent to military operations.

Using the field measurements in this study, it is possible to construct a valid mathematical terrain model of a field of drumlins distributed over an assumed level plain. Statistical data on distribution and spacing of drumlins are available from published sources (particularly Reed and others, 1962; Vernon, 1966; and Chorley, 1959). The model, representative of several glaciated areas of the earth, would be useful in evaluation of, at least, military mobility and intervisibility problems.

If the present data were augmented by field measurements of landforms intervening between drumlins (e.g., outwash plain, moraines, kames, kettles, recent drainageways), a detailed model of broad tracts of glaciated terrain throughout the Northern Hemisphere could be constructed.

BIBLIOGRAPHY

Morphometry

Chorley, R. J., 1959, The Shape of Drumlins; Jour. Glaciology, v. 3, no. 25, p. 339-344.

Reed, B., and others, 1962, Some Aspects of Drumlin Geometry; Am. Jour. Sci., v. 260, p. 200-210.

Smalley, I. J. and Unwin, D. J., 1968, The Formation and Shape of Drumlins and their Distribution and Orientation in Drumlin Fields; Jour. Glaciology, v. 7, no. 51, p. 377-390.

Vernon, Peter, 1966, Drumlins and Pleistocene Ice Flow over the Ards Peninsula/Strangford Lough Area, County Down, Ireland; Jour. Glaciology, v. 6, no. 45, p. 401-409.

Areal

Alden, Wm. C., 1924, Physical Features of Central Massachusetts; U. S. Geol. Survey Bull. 760-B.

Ebers, E., 1925, Die Bisherige Ergebnisse der Drumlinforschung. Eine Monographie der Drumlins; Neues Jahrbuch für Mineralogie usw., Beilageband LIII. Abt. B.

----, 1926, Das Eberfinger Drumlinfeld; Geognisches Jahresheft 39, 47-85.

Früh, J., 1896, Die Drumlinlandschaft mit Spezieller Berücksichtigung des Alpinen Vorlandes; Jahresbericht der St. Gallischen Naturwissenschaftlichen Gesellschaft, 1894-1895.

Hansen, W. R., 1956, Geology and Mineral Resources of the Hudson and Maynard Quadrangles, Mass.; U. S. Geol. Survey Bull. 1038.

Rothpletz, A., 1917, Die Osterseen und der Isarvorlandgletscher; Landeskundl. Forschungen, Geographische Gesellschaft, München, heft 24, p. 99-314.

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Historical

Barton, G. H., 1893, Remarks on Drumlins; Proc. of the Boston Soc. of Natural History, no. 26.

Bryce, J., 1833; Jour. Royal Geol. Soc. of Dublin, v. 1, p. 37.

Charlesworth, J. K., 1957, The Quaternary Era with Special Reference to Its Glaciation; two volumes, London: Edward Arnold.

Close, M. H., 1866, Notes on the General Glaciation of Ireland; Jour. Royal Geol. Soc. of Ireland, I, 207-42, p. 231.

Davis, W. M., 1884, The Distribution and Origin of Drumlins; Am. Jour. Sci., 3rd Ser., 28, p. 407-416.

Hall, J. (Sir), 1815, Revolutions of the Earth's Surface; Trans. Royal Soc. of Edinburgh, 7, 139-212, p. 169.

Drumlin No.	Orient.	LONGITUDINAL AXIS (I) Length Stoss	Lee	Total	Asymm Ratio	Height Stoss	Lee	Mean	HIGHPOINT CROSS (II) Length Left	Right	Total	Asymm Ratio	Height Left	Right	Mean	Axial Ratio	Mean Height
1	005	525	711	1236	1.35	48	47	48	250	351	601	1.40	55	44	50	2.06	49
2	353	670	384	1054	0.57	61	78	70	415	389	804	0.94	113	69	91	1.31	80
3	320	1044	1469	2513	1.41	140	146	143	672	758	1430	1.13	135	146	141	1.76	142
4	004	1365	1684	3049	1.23	186	173	180	778	1189	1967	1.53	179	198	189	1.55	184
5	360	931	1105	2036	1.19	99	86	93	452	534	986	1.18	86	99	93	2.06	93
6	003	1419	689	2108	0.49	80	78	79	688	664	1352	0.97	80	118	99	1.56	89
7	329	940	861	1801	0.92	99	49	74	500	1081	1581	2.16	33	100	67	1.14	70
8	335	1491	798	2289	0.54	117	130	124	870	678	1548	0.78	89	107	98	1.48	111
9	327	956	725	1681	0.76	77	73	75	570	465	1035	0.82	65	75	70	1.62	73
10	358	649	485	1134	0.75	63	90	77	361	492	853	1.36	63	106	85	1.33	81
11	350	844	1565	2409	1.85	95	85	90	601	443	1044	0.74	83	77	80	2.31	85
12	347	506	757	1263	1.50	39	75	57	522	522	1044	1.00	73	35	55	1.21	56
13	369	1183	1140	2323	0.96	144	152	148	648	988	1636	1.52	177	191	184	1.42	166
14	013	1063	1051	2114	0.99	163	83	123	931	1111	2042	1.19	146	198	172	1.04	148
15	323	978	818	1796	0.84	88	94	91	799	569	1368	0.71	81	87	84	1.31	88
16	319	1090	970	2060	0.89	100	109	105	833	566	1399	0.68	98	92	95	1.47	100
17	346	1006	812	1818	0.81	77	88	83	679	466	1145	0.69	94	51	73	1.59	78
		Totals		32884							21835						
		Means		1923	1.00						1284	1.11				1.54	100

APPENDIX A. Dimensions of individual drumlins - HUDSON AREA (Axes I and II)
(See Figure 1 for locations).

Drumlin No.	STOSS CROSS (III)							LEE CROSS (IV)							Mean
	Length				Height			Length				Height			
	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Height
1	280	274	554	0.98	28	30	29	282	139	421	0.49	31	10	21	25
2	385	471	856	1.22	83	80	82	329	384	713	1.17	54	49	52	67
3	504	668	1172	1.33	85	96	91	681	615	1296	0.90	100	49	75	83
4	856	92	948	0.11	121	4	63	685	963	1648	1.41	120	114	117	90
5	389	200	589	0.51	51	43	47	403	421	824	1.05	50	67	59	53
6	607	581	1188	0.96	41	66	54	380	324	704	0.85	32	46	39	47
7	374	655	1029	1.75	25	90	58	338	388	726	1.15	10	43	27	43
8	484	384	868	0.79	51	19	35	833	773	1606	0.93	83	110	97	66
9	393	439	832	1.12	65	62	64	678	545	1223	0.80	56	61	59	62
10	396	554	950	1.40	34	71	53	131	388	519	2.96	11	73	42	48
11	497	452	949	0.91	55	63	59	307	582	889	1.90	36	56	46	53
12	623	536	1159	0.86	69	17	43	115	592	707	5.15	24	20	22	33
13	457	469	926	1.03	60	109	85	531	1050	1581	1.98	94	130	112	99
14	860	896	1756	1.04	131	142	137	653	435	1088	0.67	45	69	57	97
15	437	378	815	0.86	76	57	67	810	817	1627	1.01	47	44	46	57
16	392	703	1095	1.79	74	79	77	840	574	1414	0.68	26	54	40	59
17	830	515	1345	0.62	51	36	44	405	344	749	0.85	37	32	35	40
	Totals		17031							17735					
	Means		1002	1.02						1043	1.41				60

APPENDIX A. Dimensions of individual drumlins - HUDSON AREA (Axes III and IV)
(cont'd.) (See Figure 1 for locations).

Drumlin No.	LONGITUDINAL AXIS (I)								HIGHPOINT CROSS (II)							Axial Ratio	Mean Height
	Orient.	Length				Height			Length				Height				
		Stoss	Lee	Total	Asymm Ratio	Stoss	Lee	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean		
1	345	564	955	1519	1.69	91	95	93	446	420	866	0.94	96	80	88	1.75	91
2	360	577	1619	2196	2.81	83	118	101	244	295	539	1.21	82	84	83	4.07	92
3	348	834	1131	1965	1.36	56	110	83	503	490	993	0.97	90	79	85	1.98	84
4	356	1007	1123	2130	1.12	21	32	27	519	602	1121	1.16	28	27	28	1.90	27
5	360	1449	1443	2892	1.00	104	143	124	612	650	1262	1.06	117	125	121	2.29	122
6	357	318	285	603	0.90	30	32	31	196	138	334	0.70	50	43	47	1.81	39
7	342	1270	448	1718	0.35	99	127	113	478	345	823	0.72	109	61	85	2.09	99
8	346	1128	1052	2180	0.93	101	61	81	329	590	919	1.79	86	87	87	2.37	84
9	305	352	514	866	1.46	88	68	78	246	340	586	1.38	88	81	85	1.48	81
		Totals		16069							7443						
		Means		1785	1.29						827	1.10				2.19	80

APPENDIX B. Dimensions of individual drumlins - WEEDSPORT AREA (Axes I and II) (See Figure 2 for locations).

Drumlin No.	STOSS CROSS (III)							LEE CROSS (IV)							Mean Height
	Length				Height			Length				Height			
	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	
1	362	552	914	1.52	55	59	57	432	293	725	0.68	68	24	46	52
2	266	326	592	1.23	69	76	73	365	265	630	0.73	11	61	36	55
3	298	675	973	2.27	57	82	70	515	531	1046	1.03	53	52	53	62
4	396	367	763	0.93	22	16	19	366	370	736	1.01	14	15	15	17
5	526	453	979	0.86	68	88	78	640	551	1191	0.86	89	105	97	88
6	187	169	356	0.90	44	49	47	61	178	239	2.92	23	48	36	42
7	345	310	655	0.90	61	53	57	523	409	932	0.78	99	57	78	68
8	309	504	813	1.63	53	51	52	364	363	727	1.00	49	30	40	46
9	196	239	435	1.22	64	67	66	189	275	464	1.46	67	37	52	59
	Totals		6840							6690					
	Means		720	1.27						743	1.16				

APPENDIX B. Dimensions of individual drumlins - WEEDSPORT AREA (Axes III and IV)
(cont'd) (See Figure 2 for locations).

Drumlin No.	Orient.	LONGITUDINAL AXIS (I) Length				Height			HIGHPOINT CROSS (II) Length				Height			Axial	Mean
		Stoss	Lee	Total	Asymm Ratio	Stoss	Lee	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Ratio	Height
1	337	977	1319	2296	1.35	79	142	111	325	438	763	1.35	72	90	81	3.01	96
2	343	772	817	1589	1.06	76	81	79	285	482	767	1.69	78	105	92	2.07	85
3	327	845	781	1626	0.92	112	78	95	394	391	785	0.99	88	57	73	2.07	84
4	344	744	1686	2430	2.27	154	213	183	693	638	1331	0.92	158	132	145	1.83	164
5	347	625	1013	1638	1.62	87	111	99	227	814	1041	3.59	70	135	103	1.57	101
6	326	592	972	1564	1.64	58	75	67	327	436	763	1.33	77	80	79	2.05	73
7	334	489	1292	1781	2.64	60	66	63	273	309	582	1.13	68	71	70	3.06	66
8	315	581	821	1402	1.41	58	80	69	478	526	1004	1.10	110	107	109	1.40	89
9	339	780	1172	1952	1.50	110	147	129	604	644	1248	1.07	147	116	132	1.56	130
10	339	524	936	1460	1.79	75	75	75	239	366	605	1.53	74	86	80	2.41	78
11	331	853	1144	1997	1.34	101	67	84	445	458	903	1.03	99	92	96	2.21	90
12	338	563	1350	1913	2.40	72	100	86	562	543	1105	0.97	109	99	104	1.73	95
13	333	727	1061	1788	1.46	63	61	62	180	348	528	1.93	63	82	73	3.39	67
Totals				23436							11425						
Means				1803	1.65						879	1.43				2.18	94

APPENDIX C. Dimensions of individual drumlins - EBERFING AREA (Axes I and II)
(See Figure 3 for locations).

Drumlin No.	STOSS CROSS (III)							LEE CROSS (IV)							Mean
	Length				Height			Length				Height			Mean
	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Height
1	262	272	534	1.04	44	42	43	369	644	1013	1.75	65	96	81	62
2	223	319	542	1.43	59	54	57	175	428	603	2.45	37	68	53	55
3	273	262	535	0.96	59	64	62	362	189	551	0.52	56	29	43	53
4	540	566	1106	1.05	64	61	63	463	512	975	1.11	96	85	91	77
5	397	489	786	1.23	52	87	70	158	520	678	3.29	17	88	53	62
6	334	400	734	1.20	51	64	58	497	210	707	0.42	39	44	42	50
7	230	258	488	1.12	34	46	39	267	292	559	1.09	51	53	52	46
8	228	379	607	1.66	43	83	63	626	458	1084	0.73	102	96	99	81
9	406	439	845	1.08	80	63	72	509	637	1146	1.25	102	71	87	80
10	164	260	424	1.59	36	49	43	332	255	587	0.77	63	48	56	50
11	256	334	590	1.30	46	69	56	318	294	612	0.92	62	64	63	61
12	579	420	999	0.73	78	97	88	412	438	850	1.06	71	83	77	83
13	143	582	725	4.07	39	96	68	284	293	577	1.03	51	51	51	60
	Totals		8915							9942					
	Means		686	1.42						765	1.26				63

APPENDIX C. Dimensions of individual drumlins - EBERFING AREA (Axes III and IV)
(cont'd) (See Figure 3 for locations).

Drumlin No.	LONGITUDINAL AXIS (I)								HIGHPOINT CROSS (II)							Axial Ratio	Mean Height
	Orient.	Length				Height			Length				Height				
		Stoss	Lee	Total	Asymm Ratio	Stoss	Lee	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean		
1	327	531	910	1441	1.71	88	65	77	259	345	604	1.33	86	94	90	2.39	83
2	320	656	600	1256	0.91	59	55	57	294	279	573	0.95	61	53	57	2.19	57
3	318	769	457	1226	0.59	111	53	82	142	444	586	3.13	2	134	83	2.09	83
4	315	712	919	1631	1.29	161	134	148	442	428	870	0.97	120	125	123	1.87	135
5	287	513	791	1304	1.54	56	127	92	588	427	1015	0.73	115	123	119	1.28	105
6	315	839	426	1265	0.51	73	16	45	300	307	607	1.02	58	38	48	2.08	46
7	318	756	1242	1998	1.64	132	95	114	391	353	744	0.90	124	85	105	2.69	109
8	292	989	1039	2028	1.05	140	125	133	408	690	1098	1.69	99	150	125	1.85	129
9	314	595	940	1535	1.58	128	117	123	391	615	1006	1.57	101	169	135	1.53	129
10	348	509	710	1219	1.39	106	52	79	221	436	657	1.97	69	97	83	1.86	81
		Totals		14903							7760						
		Means		1490	1.22						776	1.43				1.98	96

APPENDIX D. Dimensions of individual Drumlins - BODANRÜCK AREA (Axes I and II) (See Figure 4 for locations).

Drumlin No.	LONGITUDINAL AXIS (I)								HIGHPOINT CROSS (II)							Axial	Mean
	Orient.	Length				Height			Length				Height				
		Stoss	Lee	Total	Asymm Ratio	Stoss	Lee	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Ratio	Height
1	327	531	910	1441	1.71	88	65	77	259	345	604	1.33	86	94	90	2.39	83
2	320	656	600	1256	0.91	59	55	57	294	279	573	0.95	61	53	57	2.19	57
3	318	769	457	1226	0.59	111	53	82	142	444	586	3.13	32	134	83	2.09	83
4	315	712	919	1631	1.29	161	134	148	442	428	870	0.97	120	126	123	1.87	135
5	287	513	791	1304	1.54	56	127	92	588	427	1015	0.73	115	123	119	1.28	105
6	315	839	426	1265	0.51	73	16	45	300	307	607	1.02	58	38	48	2.08	46
7	318	756	1242	1998	1.64	132	95	114	391	353	744	0.90	124	85	105	2.69	109
8	292	989	1039	2028	1.05	140	125	133	408	690	1098	1.69	99	150	125	1.85	129
9	314	595	940	1535	1.58	128	117	123	391	615	1006	1.57	101	169	135	1.53	129
10	348	509	710	1219	1.39	106	52	79	221	436	657	1.97	69	97	83	1.86	81
		Totals		14903							7760						
		Means		1490	1.22						776	1.43				1.98	96

APPENDIX D. Dimensions of individual Drumlins - BODANRÜCK AREA (Axes I and II) (See Figure 4 for locations).

Drumlin No.	Orient.	LONGITUDINAL AXIS (I)							HIGHPOINT CROSS (II)							Axial	Mean
		Length				Height			Length				Height				
		Stoss	Lee	Total	Asymm Ratio	Stoss	Lee	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Ratio	Height
								CATO									
1	339	2220	2284	4504	1.03	161	96	129	538	445	983	0.83	160	167	164	4.58	146
								CAYUGA									
1	345	1346	3422	4768	2.54	102	76	89	376	336	712	0.89	95	100	98	6.70	93
2	348	790	1053	1843	1.33	95	70	83	363	317	680	2.15	79	85	82	2.71	82
		Totals		6611							1392						
		Means		3306	1.94						696	1.52				4.71	88
								ROSENHEIM									
1	040	741	1048	1789	1.41	57	69	63	469	422	891	0.90	31	87	59	2.01	61
2	021	1945	1579	3524	0.81	51	48	50	389	389	778	1.00	33	26	30	4.53	40
3	040	990	1031	2021	1.04	50	49	50	581	499	1080	0.86	83	42	63	1.87	56
		Totals		7334							2749						
		Means		2445	1.09						916	0.92				2.80	52

APPENDIX E. Dimensions of individual drumlins - CATO, CAYUGA, and ROSENHEIM AREAS (Axes I and II)

Drumlin No.	STOSS CROSS (III)							LEE CROSS (IV)							
	Length				Height			Length				Height			Mean
	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Left	Right	Total	Asymm Ratio	Left	Right	Mean	Height
								CATO							
1	340	341	681	1.00	97	104	101	586	511	1097	0.87	114	107	111	106
								CAYUGA							
1	352	384	736	1.09	83	86	85	322	434	756	1.35	74	73	74	80
2	315	253	568	0.80	82	65	74	227	328	555	1.44	50	66	58	66
		Totals	1304							1311					
		Means	652	0.95						656	1.40				73
								ROSENHEIM							
1	Not measured in the field							460	375	835	0.82	46	66	56	56
2	497	541	1038	1.09	32	63	48	255	521	776	2.04	12	36	24	36
3	451	401	855	0.89	61	28	45	Not measured in the field							45
		Totals	1893							1611					
		Means	947	0.99						806	1.43				46

APPENDIX E. Dimensions of individual drumlins - CATO, CAYUGA, and ROSENHEIM AREAS (Axes III and IV)